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Review

State of the art and applications in archaeological underwater 3D recording and mapping

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ABSTRACT

Since remote times, mankind has been bound to water bodies and evidence of human life from the very beginning hides under the water level, off the coasts, under shallow seas or deep oceans, but also inland water bodies of countries all around the world. Recording, documenting and, ultimately, protecting underwater cultural heritage is an obligation of mankind and dictated by international treaties like the Convention on the Protection of the Underwater Cultural Heritage that fosters and encourages the use of "non-destructive techniques and survey methods in preference over the recovery of objects". 3D digital surveying and mapping techniques represent an invaluable set of effective tools for reconnaissance, documentation, monitoring, but also public diffusion and awareness of underwater cultural heritage (UCH) assets. This paper presents an extensive review over the sensors and the methodologies used in archaeological underwater 3D recording and mapping together with relevant highlights of well renowned projects in 3D recording underwater.

1. Introduction and scope

This paper focuses on three-dimensional (3D) digital recording techniques for underwater archaeology, with the aim to present an up-to-date comprehensive review of modern sensors and techniques for reconnaissance, documentation and monitoring of underwater cultural heritage (UCH[1]) sites and assets. Firstly, a brief introduction on the needs for 3D documentation underwater is given, afterward the paper summarises the main physical characteristics of water, to then provide an overview of active and passive, optical as well as acoustic sensors in use today. An overview of techniques and methods is subsequently reported, together with relevant highlights of well renowned projects in 3D recording underwater.

1.1. Water and human life

Water is the most important element for human beings as it is essential for their life. Indeed, since remote times, mankind has been bound to water bodies either in their natural forms, such as oceans, lakes, rivers, wetlands, or in their man-made counterparts, such as structures, flumes, channels, basins, dams etc. After all, planet Earth is mostly covered by water rather than lands, and freshwater is necessary for humankind hydration, thus humans on earth have always relied on a drinkable water resource very close to their settlements.

Water has also been an important resource for irrigation and, above all, an important means for transportation and trade, other than being the most effective way to explore new continents in ancient times.

Evidence of human life from the very beginning hides under the water level, off the coasts, under shallow seas or deep oceans, but also inland water bodies of countries all around the world. In other cases, even subterranean water bodies witness venerated sites used by ancient civilizations for sacrificial offerings or aquatic cemeteries, such as the case of cenotes in the Maya civilization [1].

1.2. UCH: a property belonging to everyone

Today, there is much more heritage underwater than it might be thought by most people, but the significance of the testament provided by this heritage is unfortunately still underestimated. Not only is this underestimation a lost opportunity to know our

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[1] A complete list of acronyms is given in the glossary at the end of the manuscript.

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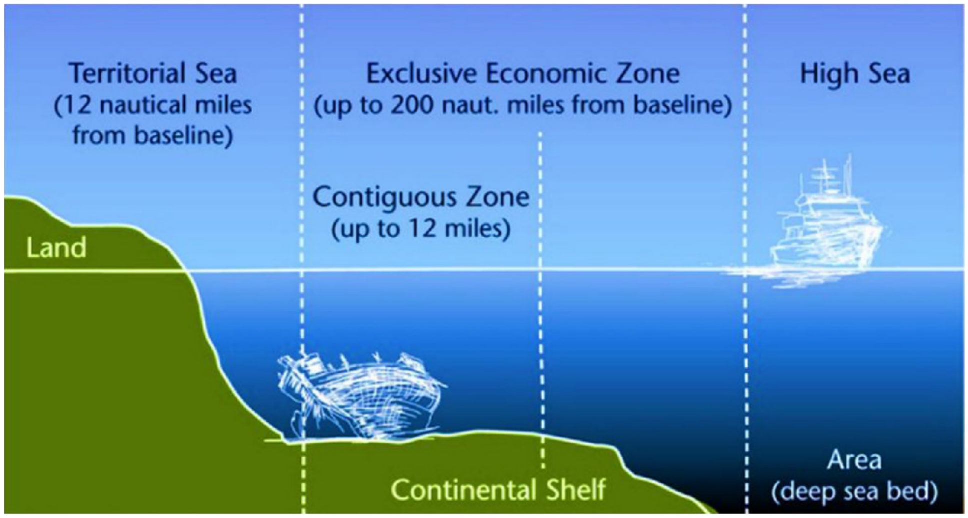

Fig. 1. Maritime zones according to the Law of the Sea, © UNESCO [185].

past and ourselves better, but it is also the cause of scarce application or complete lack of laws able to protect the underwater heritage. The deficiency of a proper legal protection of underwater heritage has unfortunately brought to some exemplary cases of looting and commercial exploitation, or sometimes, even destruction from incidental human activities at sea such as dredging and fishing [2]. In addition, it is extremely difficult to monitor and guard underwater heritage either in shallow or in deep waters from looters.

Recognising the importance of UCH, to the end of its common shared protection, international organizations have been striving to find a solution to protect the submerged cultural heritage, especially in international context. The path to reach a first agreement was hard and long. In the wake of what had been previously acknowledged by the UNESCO Convention for the Protection of Cultural Property in the Event of Armed Conflict (Hague Convention of 1954), the underwater cultural heritage was recognised as cultural property belonging to any people whatsoever, a cultural property at risk of looting and destruction.

In 1982, The United Nations Convention on the Law of the Sea (UNCLOS) divided the world's seas into different zones according to their distance from the coast (Fig. 1); however, underwater cultural heritage was not a key topic of this agreement.

It was not until 1994 that a first specific treaty on underwater cultural heritage was adopted by the International Law Association (ILA) in Buenos Aires in the form of a draft of the Convention on the Protection of the Underwater Cultural Heritage.

Table 1 summarises the main historical evolution of international treaties considering the underwater cultural heritage. To set out a global treaty on the Protection of the Underwater Cultural Heritage with a binding nature also outside the territorial seas, it was necessary to wait until 2001, when UNESCO assumed the responsibility for creating a binding legal instrument based on the consideration of the ILA draft and the ICOMOS Charter, and ended up with the Convention on the Protection of the Underwater Cultural Heritage adopted in 2001 [3].

The Convention on the Protection of the Underwater Cultural Heritage sets out basic principles for the protection of UCH and provides a detailed state cooperation system, based on guidelines and rules for the treatment and research of underwater cultural heritage. This text can be considered as the most comprehensive effort existing today to establish rights and responsibilities of nations with respect to UCH. Unfortunately, this treaty has been ratified by only 58 states out of 193 UNESCO members up to now.

1.3. *The need for recording in underwater archaeology*

Underwater archaeology is a complex process comprising different tasks that aim to describe and interpret the physical traces left by past ways of life [4]. The main aim of underwater archaeology is explanation, carried out through an investigative process based on the analysis and study of the evidences found on an underwater archaeological site, but it is also about assessing, stabilising, managing, monitoring and preserving these traces [5]. The discovery of underwater archaeological sites can be accidental, such as when a recreational diver finds a clear evidence (e.g. the famous Riace bronzes were found by a tourist snorkelling few tens of metres off the coast of Riace, Italy), or when a subsea construction work is carried out, or can be the result of a scientific reconnaissance aimed at discovering of specific remnants underwater after a desk based research, as stressed by a recent European project on UCH [5]. 3D recording, mapping and modelling are key tools for assessing the state of preservation of the heritage asset and, above all, for understanding whether the asset is under natural (i.e. strong currents, bio-deterioration e.g. from wood borers) or manmade threats (i.e. looting or fishnets) that require some forms of urgent intervention for its protection. Indeed, as mentioned by the Convention on the Protection of UCH, in situ preservation should be considered as first option before allowing and engaging in any activities directed at it. Therefore, among the operational guidelines and rules proposed by the convention, the documentation of underwater heritage sites is of paramount importance[2]. In particular, chapter III – Operational protection of the Operational Guidelines for the Convention on the Protection of the Underwater Cultural Heritage [6] states: "Activities directed at underwater cultural heritage must use non-destructive techniques and survey methods in preference over the recovery of objects" [...] "the methods and techniques used must be as non-destructive as possible and contribute to the preservation of the remains". Moreover, the Convention endeavours to raise public awareness and sharing of any result achieved from activity directed at underwater cultural heritage. To this end, the Convention stresses and highlights how information should be always addressed to the scientific community, as well as to the general public.

[2] Rules 26–27 of the ANNEX to the convention of 2001 – "Rules concerning activities directed at underwater cultural heritage".

Table 1
International treaties.

Date	Organisation	Document	Jurisdiction
1956	UNESCO	Recommendation on International Principles Applicable to Archaeological Excavations	Territorial seas
1982	UN	United Nations Convention on the Law of the Sea (UNCLOS)	Territorial seas
1994	ILA	Draft of the Convention on the Protection of the Underwater Cultural Heritage	Territorial to high seas (no binding nature)
1996	ICOMOS	Charter on the protection and management of underwater cultural heritage	Territorial to high seas (no binding nature)
2001	UNESCO	Convention on the Protection of the Underwater Cultural Heritage	Territorial to high seas

In this context, 3D digital surveying and modelling techniques represent an invaluable set of effective tools for reconnaissance, documentation, monitoring, but also public diffusion and awareness of UCH assets, through for example, virtual reality headsets, serious games, etc. [7,8]. Depending on the archaeological needs and on environmental conditions such as depth or water turbidity, sensors, techniques and methods may need to be used differently or may even be not suitable at all. Readers who are not acquainted with 3D surveying and modelling techniques, like photogrammetry and 3D scanning, may first want to refer to [9–11].

2. Physical properties of water

Traditional surveying on land uses active or passive image techniques or devices almost entirely based on electromagnetic waves [10, 12]. Although on land these techniques have been successfully used for decades, water's physical characteristics are such that 3D modelling of underwater environments becomes much more complex or even unfeasible in certain cases.

Water is a medium inherently different from air and the first essential difference resides in the medium density. Seawater is nearly 800 times denser than air and its density is not constant through the depth, being a function of temperature, salinity and pressure.

Water, especially from the sea, has a very high conductivity, with the very well-known consequence of damaging electronic devices if not properly protected. Thus, the use of sensors underwater implies the use of special housings that must be waterproof and resist to high pressure to avoid sensor failure.

The high conductivity and permittivity of water has also the effect of attenuating electric waves to a great extent, making radio signals seldomly used underwater for communication and ranging measurements. Recording data in the water occurs nowadays mainly using optical or acoustic sensors. Hence, it is imperative that the properties of water for both these wave forms should be examined.

2.1. Optical properties

The refractive index of water is higher than air being about 1.33 for freshwater and 1.34–1.35 for salt water at 25°C. One of the most known optical phenomena concerning water is that any ray of light is deflected after hitting the water surface depending on the angle of incidence. The phenomenon is common to any surface separating media with different refractive indexes (Snell's law).

Light attenuation in water is ruled by scattering and absorption. Pure waters (either fresh or salty) are optically pure media totally exempt from any suspended particles; in pure water, light is absorbed only because of interaction of light with molecules and ions [13]. Long visible wavelengths, such as red light, are absorbed first, short visible wavelengths, like blue, last. For this reason, only 1% of the light entering the sea reaches 100 m depth.

When suspended particles or sediments resulting from natural phenomena or human activities are present in water, a further light attenuation is present, and water is said to be turbid, cloudy. The more the particles, the higher the turbidity. Depending on the characteristics of these particles (such as size and colour), light is absorbed rapidly and selectively (wavelength dependency), thus affecting the water colour. Turbidity of water is generally quantified using the Secchi distance, an old and simple method introduced in 1865 [14]. A white circular disk is immersed in water and the distance at which the disk is not more visible is defined as one Secchi distance.

2.1.1. The geometry of two-media photogrammetry

The term "two-media photogrammetry" implies that photogrammetric images are taken through two media, i.e. in this case air and water, existing between the camera lens and the object. In nature, the water surface is rarely static, ripples and waves make the angle of incidence for a specific optical ray continuously varying in time, leading to unique distortions when images of immersed objects are taken from outside the water. Moreover, the refraction of natural illumination is spatio-temporally varying due to the waves on the water surface, thus creating the characteristic illumination patterns to the object below (refraction) and above (reflection) the water surface. For this reason, through water optical measurement methods usually present many limitations. Indeed, the geometry of through-water photogrammetric measurements has been investigated and mathematically formulated by many authors [15–23]. For static and flat separation surfaces, such as when the image is taken behind a glass, rigorous modelling was successfully adopted by many authors who have explicitly modelled the additional distortion effects caused by refraction [24,25], traced the optical path through the various media interfaces [26,27] or let the typical photogrammetric calibration model [28] to compensate for the additional refraction effects of water [29,30]. According to the basic optical principles and equations, accurate through-water photogrammetry is theoretically possible also for a non-static water surface. However, as far as the orientation of the water surface changes continuously with respect to the camera, the refraction effect in through water applications cannot be accurately compensated for [15]. In practice, although two-media photogrammetric applications produce results with lower accuracy requirements, they have great potential for documenting objects in shallow waters (section 4.1.1).

2.2. Acoustic properties

While water absorbs electromagnetic waves very quickly, it does transmit sound very well. Sound is a mechanical wave of pressure and displacement originating from continuous vibrations in a surrounding medium. Sound is used in SONAR, a technique well known in nature to animals like marine mammals for communication and navigation.

Sonar systems use sound propagation between a transmitter and a receiver, and are used to remotely sense the interior of bodies of water, their floor and even the structures beneath the bottom. Indeed, when the sound wave encounters a surface interface between media with different physical characteristics, for example sea water and a sandy seabed, part of the energy is reflected, part is refracted and keeps travelling in the new media after a bending of the direction of propagation, according to Snell's law, and the remaining is scattered. The energy returned to the sonar device can provide information about the physical properties of the object.

Humans have known the principles of modern SONAR for hundreds of years. In 1490, Leonardo da Vinci, aware of the very good propagation of sound in the water, had already suggested the use of an underwater tube to listen and discover approaching ships [31]. But it is after the Titanic struck an iceberg that patents for active systems able to detect objects and their distance were filed [32].

Sound is transmitted through gases, plasma, and liquids as longitudinal waves, also called compression waves. Like optical rays that undergo Snell's law, also sound waves are reflected, refracted, scattered and attenuated by spreading and absorption in the medium through which they travel. Acoustic waves, are spread as concentric spherical surfaces, whose intensity is inversely proportional to the square of the distance from the source (4th power when the sound is back reflected to the receiver). Readers who want a more comprehensive introduction to SONAR principles and applications may want to read Hodges [33] and Lurton [34].

3. Sensing and recording the underwater world

Sensing and recording the underwater world is an important part of archaeological investigations. These should always follow a well-defined sequence of tasks in a project that should be properly designed [4]. Through time, archaeologists have used different techniques for recording UCH [35,36], clearly aiming as much as possible at non-destructive and non-subjective methods, which spanned from simple sketches, up to analogue photography or video, to then come to the most recent 3D digital techniques based on digital sensors.

Sensors may be used applying different techniques that provide objective methods of investigation only if they are calibrated, characterised, and tested in real environment.

In the following sections, an overview of the currently available sensors is provided. Most techniques used for 3D recording underwater are based on optical and acoustic sensors, tailored to fulfil needs of a certain range of applications typically for short or long ranges, i.e. shallow or deep water. Given the complexity and variety of topics involved, it is a clear intention of the authors to critically report the salient features for each technology, providing clear links to the practice of 3D modelling for underwater archaeology.

3.1. Optical sensors

Optical sensors use light in the visible spectrum band as their main source of record. This is a very small part of the electromagnetic spectrum. For underwater applications, there are many kinds of optical sensors available. As for sensors working on-land, they are broadly categorized into passive and active sensors [10,37] in the sense that the passive sensors record radiation which comes from another source (sunlight, flash unit, lamps, etc.) while active ones produce their own radiation, which is cast on the object of interest and the sensor records the reflected amount of this radiation. Very few models of optical sensors have been specifically manufactured to work underwater. Consequently, specialised, and normal sensors are considered as an option, provided they may be modified to perform underwater. This implies the use of special water tight housings, which are designed to protect the sensors.

As already mentioned in section 2, the underwater environment conditions are often characterized by non-uniform lighting, poor visibility, due to scattering and absorption in the medium [38,39].

Both active and passive techniques suffer from scattering and absorption in the medium, which decreases image contrast and attenuates light intensity. To reduce the negative effect of backscattering when dealing with active sensors, different solutions have been proposed, based on polarization, spatial, time and spectrum discriminations [40,41].

3.1.1. Passive optical sensors

Passive optical sensors normally used for photogrammetric and computer vision applications on land, above the water, consist of digital cameras that may be either specifically built for metric purposes or simply consist of off-the-shelf digital cameras, as it is often the case in close-range photogrammetry. More specialised passive optical sensors are used on board satellites. Example of metric cameras for aerial photogrammetry are the Vexcel Ultracam [42], or Leica DMC III [43], while some examples for close range photogrammetry are the Rolleimetric [44], the Geodetic Services V-STARS [45] and the ALPA camera [46].

Manufacturing cameras for photogrammetry needs to guarantee several requirements, among which the most important are a high mechanical stability, e.g. not moving optics, a homogeneous high-quality image across the whole sensor format, and minimised optical distortions [47,48]. Low noise and high dynamic range are also a must, as high contrast scenes are very likely to occur in an uncontrolled light environment. These cameras are generally used for highly specialised applications, that need maximum calibration stability over time as they cannot be frequently calibrated in laboratory (e.g. not to stop the surveying activity). Off-the-shelf cameras, built for general purpose photography, allow much more flexibility (i.e. interchangeable lenses, portability, lower price, etc.) but suffer from unstable camera calibration that, for some models, may even vary during the same image acquisition, as it is the case for compact and DSLR zoom cameras [49,50].

Digital cameras for underwater photogrammetry can be mainly divided in: (i) industrial single and stereo camera systems, mainly used for aquaculture and fisheries applications like AKVAsmart, formerly VICASS [51], and the AQ1 AM100 [52] or mounted on Remotely Operated Vehicles (ROV) and Autonomous Underwater Vehicles (AUV), capable of standing high pressure for automated

Fig. 2. Samples of underwater pressure housings and cameras: a: Teledyne Surveyor-HD-Pro; b: Kongsberg OE14-504 c: Imenco spinner shark; d: Leica X-U; e: Nikon AW1; f: Olympus TG-4; g: Seacam; h: Isotta; i: NiMAR.

guidance and inspections in the oil industry (Fig. 2a–c), but also used for deep archaeology photogrammetric surveys. A good summary of these stereo systems is given in Shortis et al. [53] or Shortis [30]; (ii) off-the-shelf high resolution digital cameras that are typically operated by a SCUBA diver, even though example of utilisation with submarine and AUVs are also reported [54,55].

Very few camera models are directly manufactured to operate in water (Fig. 2d–f). Most of them are compact cameras, with sealed buttons and controls, which allow them to be submerged to few metres (usually about 15 m). Although these cameras have not been extensively tested for underwater photogrammetry applications yet, retractable, motorised zoom lenses, and autofocus control, anticipate lower metric performances than cameras with prime lenses and manual focus.

More popular, and largely used underwater, are photographic cameras placed in a special housing with a flat or dome port (Fig. 2g–i). Housings can be made either of Polycarbonate, Delrin and similar resins (NiMAR, Fantasea, Ikelite, some Sea & Sea housings), or of Aluminum Anticorodal (the more expensive housings like Seacam, Easydive, Isotecnic Isotta, Subal, Nexus, Aquatica, Sea & Sea), or even a combination of the two (some Sea & Sea housings). Different materials and manufacturing procedures are used to guarantee different depth ratings. Special housings for 3D stereoscopic documentation have also been developed as, for example, the one presented in Rinaldi and Hordosch [56] that encloses two DSLR cameras.

Most diver operated housings are specific for a camera model and use mechanical control levers and wheels that allow only for the important control buttons on the camera. Conversely, some companies, i.e. Easydive [57] have housings with full electronic controls that allow for camera upgrades or even different camera models to be fitted inside a same housing with few modifications, mainly to the software controller.

Looking to the underwater scene through a flat or dome port has many optical consequences of which the most popular is that the field of view of the lens mounted on the camera is preserved in case of a dome port and reduced of a factor almost equal to the refractive index for the flat port. In general, this common rule is satisfied but there are many other factors that intervene in the optical formation of the image, some with very important practical implications, that may make the choice of a type of port with respect to another one not as trivial as described above [58,59].

3.1.2. Active optical sensors

3D active optical sensors can be regarded as systems that combine a source of light and a passive optical sensor rigidly fixed together in a common enclosure or frame, often referred to as range sensors or 3D scanners. A 3D scanner projects controlled light on the object surface, recording the shape and possibly its appearance (i.e. colour, material etc.).

Active optical sensors are broadly classified in two categories: (i) time-of-flight (ToF) 3D scanners measure (directly or indirectly) the delay between the emission and detection of light reflected by the object's surface; (ii) triangulation systems project light in a known geometric configuration and measure the direction of light from a known position [60]. More detailed technical descriptions and working principles of active optical sensors on land can be found in Blais [61], and Luhmann et al. [11].

Above the water, laser technology has been the flagship of 3D surveying for several years making it the preferred technology for large architectural and archaeological objects [62]. The time-of-flight or LiDAR techniques operate on the same principles used by conventional RADAR and SONAR systems, by transmitting short pulses of light and detecting the light reflected from objects within the receiver. Range information is obtained by measuring the time delay between the transmitted and received light pulses. The collected data can then be used to construct digital, three dimensional models useful for a wide variety of applications.

On land, 3D scanners are built as surveying instruments to be set on a tripod, generally referred to as terrestrial laser scanners (TLS) or can be mounted on a boat, vehicle or even handheld, and are referred to as mobile laser scanner (MLS), or can be mounted on an aerial vehicle, namely airborne laser scanner (ALS) [63,64].

Most terrestrial laser scanners operate at a wavelength of near-infrared and red, which, unfortunately, is absorbed by water [65,66]. On the other hand, green wavelength TLS have shown promising results in acquiring underwater data at the scale of stream bed grain size [67–70]. Hence, both airborne and underwater laser scanning systems operate with green laser beams. It should be noted that all modern bathymetric Lidar sensors can measure topography in addition to bathymetry.

The use of airborne lasers to measure bathymetry has been known for more than 40 years [71–73] however; such systems have not experienced the same development of systems used only for mapping terrestrial topography. Bathymetric LiDAR systems, which employ a blue-green wavelength of laser light to penetrate water, currently remain a very specialised and unique technology with only a handful of these systems currently in existence, and their use almost exclusively restricted to coastal waters [74,75] (Fig. 3). LiDAR survey systems are typically aircraft mounted and provide seamless, contiguous coverage between land and sea making them effective and cost-efficient technology to provide a continuous, detailed 3D elevation model along the coastline.

Bathymetric LiDAR is used to determine water depth by measuring the time delay between the transmission of a pulse and its return signal, reflected off an object. Systems use laser pulses received at two frequencies: a lower frequency infrared pulse is reflected off the sea surface, while a higher frequency green laser penetrates through the water column and reflects off the bottom. Analyses of these two distinct pulses are used to establish water depths and shoreline elevations. With good water clarity, these systems can reach depths of 50 m A bathymetric multispectral LiDAR system has been recently developed by Teledyne Optech (Fig. 3c).

The most obvious split within bathymetric Lidar sensors is between the shallow-water (< 10 m) and deep-water systems (> 10 m). The shallow-water systems tend to have less laser power

Fig. 3. Characteristic examples of bathymetric LiDAR systems: a: Chiroptera of Leica Geosystems© for shallow waters; b: HawkEye III of Leica Geosystems© for deep waters; c: Titan from Teledyne Optech©; d: Bathycopter LiDAR UAV by Riegl©.

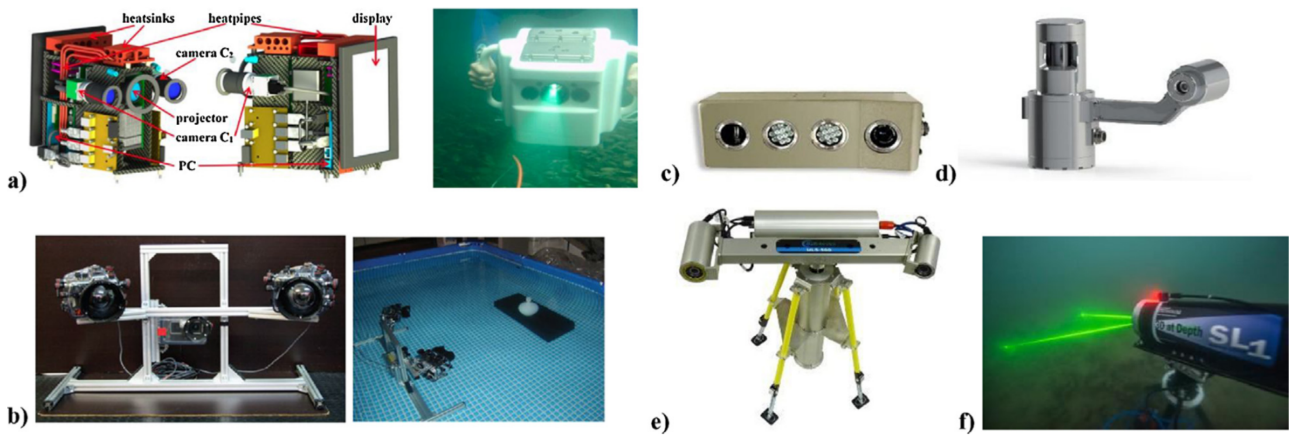

Fig. 4. Underwater active optical sensors based on structured light or laser scanning: a: a handheld fringe projection scanning device [81]; b: fringe projection system using commercial cameras and projector [82]; c: the M310UW Extended Range Laser Scanner and d: the M4000UW by NewtonLabs; e: the LS-500 triangulation based underwater laser scanner; f: the SL1 Deep sea ToF laser scanner.

per pulse, a higher measurement frequency (high resolution), smaller laser footprint diameter and a smaller receiver field of view, and can generally only measure water depths within the visible water column. The deep-water bathymetric LiDAR systems use more laser power per pulse, a lower measurement frequency (low resolution), a larger laser footprint and receiver field-of-view. These deep-water bathymetric LiDAR systems vary in depth penetration capability from between 2.0 to 3.0 times the Secchi depth measurement [76]. Bathymetric LiDAR is also used to acquire data in areas with complex and rugged shorelines where surface vessels cannot operate efficiently or safely because of rocks, kelp or breaking surf.

The most recent generation of ALB scanner systems utilise very short and narrow green laser pulses resulting in mapping large underwater surfaces in high detail (ground sampling distance < 50 cm) but reduced depth enabling their use in more detailed archaeological mapping and reconnaissance [77].

According to Mandlburger et al. [78] deriving digital surface models of seabed from ALB is a process that comprises different well defined stages: (i) echo detection and generation of a 3D point cloud from the scanner, GNSS and IMU data, (ii) strip adjustment and quality control, (iii) calculation of a water surface model for subsequent refraction correction (iv) range and refraction correction of water echoes based on the water surface model, (v) classification of surface and off-surface points (both within and outside the water body), (vi) DTM interpolation, (vii) rendering (typically hillshade, slope, local relief model, openness).

The recent work of Westfeld et al. [79] extends the refraction correction described in (iii) by investigating the effect of wave patterns on refraction and subsequently on seabed coordinate accuracy. The results of the simulations indicate that the simplified assumption of averaging wave effects often made in many (large footprint) ALB applications seems not sufficiently justified while the effect is amplified for modern LiDAR bathymetry systems, which come with much smaller footprints.

Recent advances in bathymetric LiDAR include multiple sensors on the aircraft, faster throughput to data products, reflectance calibration between flight lines, greater point density, enhancements for freshwater capture, and enhanced classification of point clouds. Additionally, thanks to the miniaturization of sensors, bathymetric LiDAR is increasingly becoming feasible even on small UAVs, as illustrated in Fig. 3d [76].

Although being a promising and effective technology for coastline topography and bathymetry, airborne LiDAR does not provide appropriate resolution and accuracy for detailed inspections and 3D modelling of underwater objects. With this aim, submersed optical active systems are used within just few metres from the object to be surveyed. Generally, these systems make use of coherent light (laser) for a better light propagation, suitable for long range acquisition [80], and for the capability to make beams highly collimated, although triangulation based systems using fringe projection techniques have been developed such as those presented in Bräuer-Burchardt et al. [81], Bruno et al. [82], Zhang et al. [83] and shown in Fig. 4.

Underwater sensors based on triangulation and time-of-flight principles scan the entire target of interest, using a sheet of light or a narrow beam. The single sheet projection is useful in several applications like underwater navigation [84], and pipe inspection [85]. Using the forward movement of the AUV, a stripe of light can provide the map of a seabed [86]. When large areas are to be scanned, multiple scan stripes are used [87]. A two-axis scanning system allows to perform a point-to-point scan on the object from a stationary platform [86,88,89]. This technique is used in marine biology, plankton study [90] and underwater holography (in-line or off-line), because it allows small-scale 3D reconstruction with high accuracy [90].

As far as completely submersed sensors are concerned, few companies have manufactured devices that operate underwater. For instance, the scanner illustrated in Fig. 4c is rated to a depth of 100 m and can scan an area up to 4 by 5 meters having a maximum distance of 5 meters. The resulting accuracy of the output, after point cloud processing, may reach 0.02 mm. For deeper surveys up to 4000 meters, scanners like the ones presented in Fig. 4d and e are existing in the market, operating by optical triangulation and reaching the accuracy of 1–10 mm, depending on the scanning distance. In Fig. 4f, a Time of Flight (ToF) system is illustrated, also rated to 3000 meters depth. Most of these scanners can be deployed in a variety of methods, including pole mounting, articulated arms, ROV/AUV or other robots and can also work in air other than in fresh or salty water.

3.2. Acoustic sensors

Similar to optical sensors classification described in section 3.1, sonar sensors are divided in active and passive. While in a passive sonar system, energy originates from a target and propagates to a receiver; in an active sonar system, waves of specific, controlled frequencies, emitted by the transmitter, reach the target to then propagate back to the receiver. Depth determination of sea floor or any other target underwater is performed with active sonar sensors called echo sounders. Such sonar systems can be as simple as a single beam omnidirectional transceiver, but most applications require directional functionality, which allows for accurate bearing determination of the target and reduced noise. Today, directionality is mostly obtained using arrays of receivers (hydrophones) to form beams in the desired direction [33]. The process of depth determination is very similar to LiDAR, presented in section 3.1.2. By precisely knowing the speed of sound in water, and measuring the time of travel of the sound, distance to the target can be easily calculated. The main problem in water is that the sound speed (approximately 1500 m/s) depends on many parameters such as salinity, temperature and pressure that may vary continuously along the sound path. For instance, a change in temperature of a single Celsius degree would cause an increase in speed of 4.6 m/s when the water temperature is 0°C and 2.5 m/s when at 21°C. For this reason, accurate sonar depth measurements need the sound velocity to be measured along the water column (sound velocity profile – SVP). An echo sounder device, in its simplest configuration, is called single-beam depth sounder or single beam echo sounder (SBES). Installed beneath the hull of a boat, or immersed from a side through a rigid pole for small vessels, an SBES is able to carry out one single depth measurement at a time and, through the combination of inertial units and GNSS systems installed on board, can provide a 3D point cloud of the sea floor.

Since the absorption of sound in water depends on sound frequency (with higher frequency absorbed first), these devices usually work with more than one frequency ranging between 12 kHz to 710 kHz (wavelengths from 125 mm to 2 mm) and can measure depths greater than 10,000 m. Higher frequencies provide better vertical resolution, but have a range of propagation limited to shallower depths than what can be achieved by lower frequencies. Point density obtained by an SBES is quite limited as they provide single one-dimensional profiles following the vessel course. To obtain a two-dimensional grid of depths, multiple adjacent lines are needed, thus it is not an effective technology when large areas need to be surveyed. Conversely Multibeam echo sounders (MBES) use arrays of transducers (multi beams) that can map a complete large swath of the seabed across the vessel track at once, thus making the surveying operations much faster and cost effective (Fig. 5). A MBES emits a fan shaped sound thanks to a transmitter that can be composed of more than a hundred projectors covering a field of view up to 240 degrees (typical angles are 130–150 degrees) beneath the vessel. Multibeam echo sounders can also be mounted so that the fan shaped sound travels horizontally, a typical configuration used for obstacle avoidance in autonomous underwater vehicles [91,92].

The depth (range) resolution of a sonar is mainly dependent on the chosen frequency and duration of the sound pulse (ping). The higher the frequency and the shorter the ping, the better the resolution. Ultimately, the vertical resolution of a sonar is determined by the bandwidth (frequency range) of the transmitter/receiver. Latest CHIRP sonars, nowadays incorporated in professional as well as many low-cost devices, use a long, swept, frequency modulated pulse that provides a larger bandwidth over the long pulse length. The returned signal is processed with advanced signal processing techniques that provide a much higher depth resolution [93].

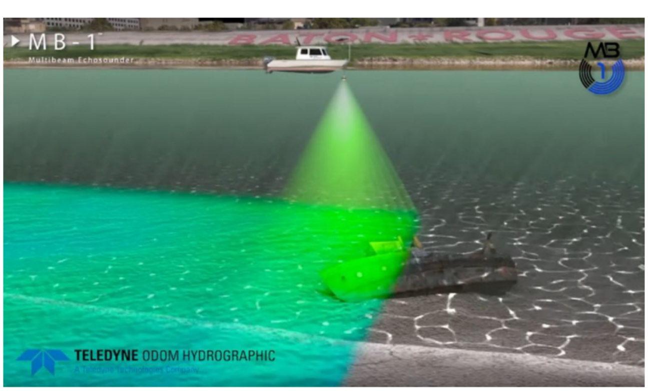

Fig. 5. A pictorial representation of a multibeam sonar system scanning a shipwreck at the bottom of a river [186].

Echo sounders are typically mounted on a moving platform, such as beneath a vessel's hull, towed by a boat or fitted within an ROV or an AUV. Spatial referencing of data is obtained through integration of GNSS system and INS for ship mounted echo sounders, while for ROV and AUV systems SLAM procedures are generally adopted [94]. A special high frequency (900 kHz) echo sounder, mounted on a mechanical scanning head, has been recently introduced by the company Teledyne Blueview (2018) [95] to operate similarly to tripod mounted terrestrial laser scanners (Fig. 6).

Other sensors using acoustic methods for underwater mapping are the side scan sonar and sub bottom profiler mainly designed to provide 2D images built upon information retrieved respectively from backscattered and penetrating sound, rather than providing depth measurements. These sensors are generally towed underwater to keep their distance from the seafloor very low, which allows for a better signal to noise ratio (SNR). Side scan sonars sends out two wide angle beams at the sides of the sensor, exploiting the side view geometry, thus the need to stay very close to seafloor. The particular geometry of transmitted and received sound allow to highlight very small changes in seafloor topography or locate objects standing out from it. Sub-bottom profilers are designed to retrieve information about 2D sections of the seafloor up to some metres, depending upon seafloor material (< 100 m for sandy floors).

As sonar and sound is used by many aquatic animals, several concerns have been raised recently regarding potential harm for fishes and marine mammals, thus making it more difficult to get permission to use acoustic systems in some countries [96]. However, SBES constitute a viable solution for determining sea bed topography in low resolution, where also no need of real texture exists in most of the cases (section 4.1).

3.3. Fusion of optical and acoustic sensors

In the literature techniques that integrate underwater data captured by acoustic and optical systems have been presented to overcome limitations of each technology. In Singh et al. [97] is presented one of the first fusion approaches using data gathered from a Roman shipwreck at about 800 m depth in the Mediterranean. There, the created photomosaics were combined with acoustic data through simple, locally defined, finite element warps. Moreover, various approaches are presented in the literature that are not specifically focused on underwater archaeological mapping, such as Lagudi et al. [98]; Drap et al. [99]; Bejarano et al. [100]; Fusiello and Murino [101]. A comprehensive review of different approaches according to the specific sensors used is presented in Ferreira et al. [102]. There, is reported that the alignment of these types of data is quite challenging and among the several open research topics, the optic-acoustic extrinsic calibration and optic-acoustic feature matching are identified as major issues which need to be further addressed. Even the fusion of visual and acoustic data in underwater applications is still not popular in underwater archaeological mapping, these techniques together with the increasing resolution of acoustic systems can bring improvements to underwater mapping, especially in turbid waters.

Table 2 summarizes the main sensor categories described so far and provides their main characteristics with links to the relative sections in the manuscript.

4. Geomatics techniques in underwater archaeological applications

Typical UCH assets (shipwrecks, architectural structures, stowed materials like amphorae etc.) vary in shape and size.

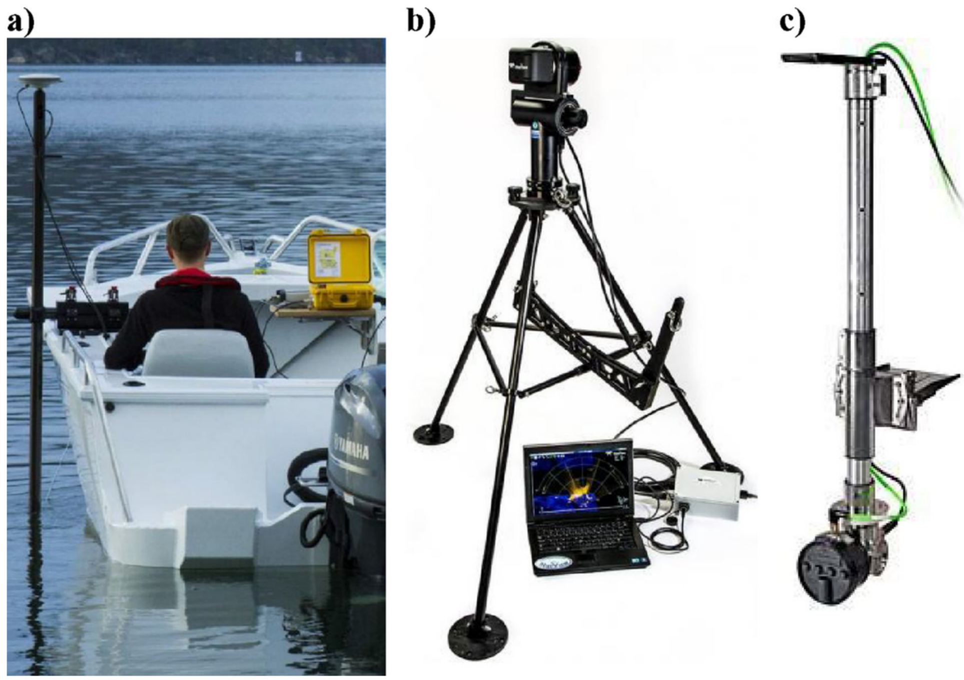

Fig. 6. Characteristic examples of SONAR systems: a: a pole mounted single beam echo sounder attached to a side of a boat from Cee hydro systems [187]; b: the Teledyne BlueView BV4100/M900 tripod mounted multibeam; c: a pole-mounted M3 multibeam from Kongsberg [188].

Table 2
Main sensor categories and typical characteristics (in grey rows, sensors are submerged while in white are outside of the water).

Sensor	Spatial resolution				Working distance	Maximum Depth	Application	Relative section
	m	dm	cm	mm				
Passive optical								
Close range			X	X	Short Limited by visibility (< 5 m)	Limited by housing systems (> 10,000 m)	3D modelling (with texture)	4.2.1 4.2.2
Airborne		X	X		Medium (From 1 m to 300 m, dependent on the platform and the camera used)	Depth depending on the turbidity of the waters (< 15 m)	Bathymetry, orthoimages of shallow water areas, reconnaissance in shallow waters	4.1.1
Active optical								
Close range			X	X	Small (< 20 m)	< 4000 m	Detailed 3D point clouds	4.2.1 4.2.2
Airborne	X	X			Medium (300 m with a swath of 100 to 250 m)	< 50 m	Bathymetry of large areas, reconnaissance	4.1.1
Acoustic								
Shipborne/AUV borne	X	X	X		> 10,000 m	> 10,000 m	Sea bed topography, reconnaissance in deep waters	4.1.2

Depending on the type of investigation or diagnostic analysis to be carried out, very detailed 3D recording may be necessary. In these cases, sensors designed for high resolution surveys, like underwater laser scanners and underwater digital cameras presented in section 3 (resolution and accuracy typically in the order of millimetres) are the most suited tools, but are limited to operate over small areas due to water transparency and design constraints, thus becoming non effective when large areas need to be surveyed; conversely, sub-meter and even meter resolution surveys may suffice for detecting a shipwreck and map large seafloor areas. In these cases, ship mounted MBES represent the state of the art solution.

Object position and orientation with respect to a global reference system (geo-referencing) may be important for several archaeological studies. Typically, 3D surveys obtained with airborne or ship mounted systems are directly georeferenced through a GNSS-INS system on board.

Conversely, mobile systems like ROV and AUV are completely submersed and hence cannot use satellite-positioning systems and typically rely on the integration of other sensors and techniques such as SLAM and acoustic positioning systems [103–106]. High-resolution surveys are most often performed in a local reference system and then geo-referenced through reference points of known coordinates.

Reference measurements are very important especially for photogrammetric techniques, which require at least a known reference length, and this is accomplished by retrieving the distance between the cameras in a stereo camera system (through a system calibration) or by measuring reference lengths and ground control points on points fixed on the seabed with traditional surveying techniques such as trilateration [107–109] or using sonar based positioning systems (e.g. [110]).

Underwater surveys are often classified according to the depth of water at which they are carried out, commonly indicated with the terms shallow and deep. The meaning of these terms is twofold depending on whether they are related to missions operated by divers or boats (but also submarines, ROVs, etc.). In the first case, the term deep is mainly referred to hazards arising from depth, typically narcotic effects, oxygen toxicity of compressed air and limited bottom time to reduce decompression sickness [111]; in the second case shallow is referred to potential hazards arising when navigating for instance in waters whose depth is close to the draft of the boat. Therefore, shallow and deep are relative terms, which may depend on the level of certification and expertise when dealing with diver operated missions or on the type of vessels in the other case. When dealing with systems that survey the bottom of a stretch of water from outside (e.g. bathymetric LiDAR), the terms shallow and deep refer to how deep the technology is able to sense underwater, function of water transparency (and active light characteristics for active systems) generally referring to shallow water for coastlines stretches up to few metres and deep up to 50 m (section 3.1.2).

As highlighted in [4,106,112,113], technology alone rarely provides the answers archaeologists are looking for; with reduced budget resources, most often characterising underwater archaeological projects, optimisation is a key factor, thus the success of an underwater archaeological project relies on reaching a synergic strategy between experts from maritime archaeology and underwater surveying.

In the following subsections, relevant works on UCH 3D recording and documentation are reported, divided according to a common coarse-to-fine approach used in archaeological investigation: a mapping of the area to be investigated at a spatial resolution sufficient for reconnaissance is followed by a detailed survey of the area of interest, typically repeated over time during the excavations or for monitoring and diagnostic purposes.

This coarse-to-fine recording is further divided considering the depth where archaeological findings are located, which for both shallow and deep waters raises peculiar technical constraints already anticipated in section 3.

4.1. Archaeological Reconnaissance and Mapping

The detection and mapping of fully submerged monuments is a time consuming and expensive process either in deep or shallow water. Reconnaissance from shallow to deep waters is carried out after preliminary historical and geological investigations to highlight potential locations of interest (such as for example submerged areas due to a local subsidence), waterlogged areas, or typical commercial routes, for example to search for sunken ships. According to Collin et al. [114], an applicable general mapping and reconnaissance methodology should utilise a DSM of the seabed (i) with sub-meter resolution to detect and identify archaeological structures and (ii) cover large areas in a sufficiently short time to be effective.

4.1.1. Mapping and Reconnaissance in shallow waters

Shallow waters represent a challenging area when dealing with reconnaissance and mapping of nearshore monuments, due to navigation hazards and practical constraints, such as boat access in areas of extremely shallow water. Shallow waters are largely affected by the energy of waves and coastal hydrodynamics that influence both the measurement process (for example due to water turbidity) and the conservation status of submerged objects (erosion, sediments, aquatic plants, oxygen, sun).

The most widely used techniques for morphological analysis of underwater archaeological areas on a regional scale are acoustic techniques, such as side-scan sonar and MBES. For example, a multiresolution approach based on a MBES system providing both 3D measurements and backscattering of the seafloor was used in the Gulf of Pozzuoli, Italy, where archaeological remains are spread over an area of several square kilometres at an average depth of some 6 m due to volcanic subsidence [115]; an example of high resolution DTM product obtained in this study is shown in Fig. 7a; D'Urso et al. [116] use a combination of SBES and MBES systems respectively for shallow and deep water at the sight of Sabratha in Lybia in a study aiming at coastal protection.

Using ship mounted MBES systems could be not cost effective when very small areas need to be investigated or with limited project budget. For this reason, low cost bathymetric solutions based on marine drones (Fig. 7b) have been investigated, featuring both acoustic and optical sensors [117,118].

In very shallow waters waterborne acoustic methods and systems have reduced performances given by the fact that the swath on the seafloor is a function of water depth, necessitating very close survey line spacing, which increases the costs accordingly. Nevertheless, compared to optical measurements, which provide higher spatial resolution than acoustic ones, acoustic systems represent the only viable solution to underwater 3D mapping when the water is not sufficiently transparent.

ALS represents an effective alternative to MBES systems, especially when long stretches of coastlines need to be surveyed, providing a seamless model of both above and under the water topography. ALS technology has found wide application in archaeological reconnaissance and documentation in shallow water with

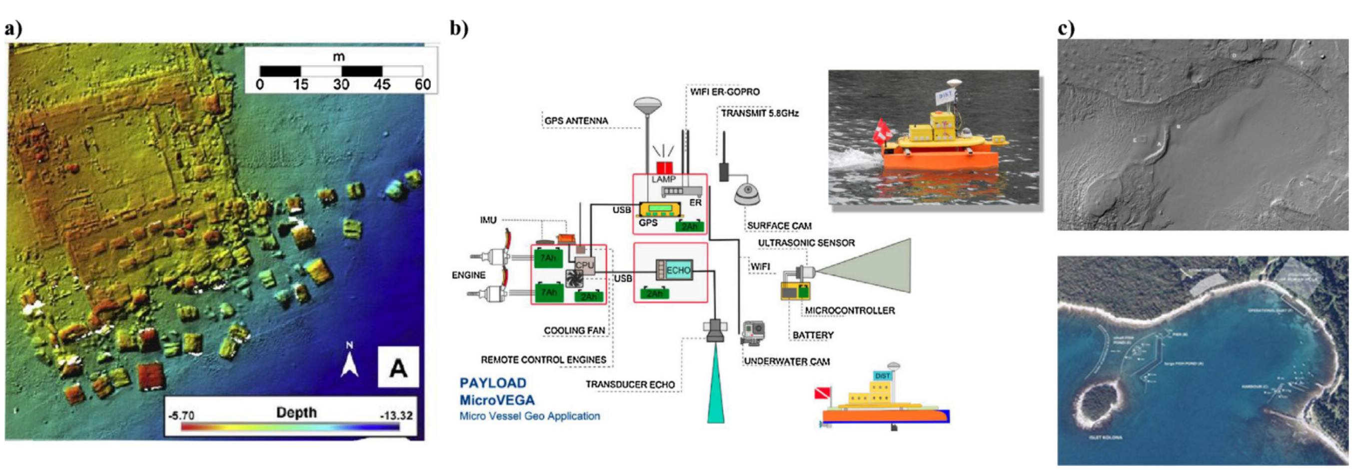

Fig. 7. Mapping of shallow water archaeological sites: a: DTM of the Villa dei Pisoni complex obtained through MBES data [115]; b: a low-cost vessel featuring different sensors for bathymetric surveys [117]; c: shaded digital surface model generated from the filtered and strip-adjusted ALB-point cloud over the Roman harbour site of Kolone, Croatia [77].

several applications in archaeological reconnaissance such as to study shipwrecks in a coral reef [119] or submerged archaeological sites [77,120].

Even if seabed measurements and DSM models could be generated using most of the ALS bathymetric systems, most of them are not designed for archaeological purposes, featuring maximum penetration of water bodies using long and high radiant energy laser pulses, thus yielding to ground sampling distances of 4–5 m [75].

The works presented by Doneus et al. [77,121] exploit most of these new tools to document and reveal submerged archaeological sites and structures in shallow waters. In Doneus et al. [77], an airborne laser scanner operating at a wavelength in the green visible spectrum (532 nm) with small footprints (0.45 m at a flying height of 450 m) and a high effective measurement rate (200 kHz) is used for scanning two case study areas in different environmental settings (one with clear sea water and one lake with turbid water). While in the clear waters penetration depth was up to 11 m, turbid water allowed only to document the upper 1.6 m of its underwater topography. Results demonstrated the potential of this technique to map submerged archaeological structures over large areas in high detail providing the possibility for systematic, large scale archaeological investigation of this environment.

Image based methods (airborne/spaceborne imagery) through the water surface are also very effective for prospection at very shallow depths. Through water image acquisition is a special case of photogrammetry where the camera is above the water surface and the object below the water surface [122]. Aerial images have been used for mapping the sea bottom with an accuracy of approximately 10% of the water depth in cases of clear waters and shallow depths, i.e. 5–10 m [123–125]. Going to more recent times, last decade has seen an increased use of UAV, and the data they provide are an excellent tool for bridging submerged and coastal structures, as well as cost and rich visual information [126]. However, the refraction phenomenon in combination with the lack of control points into the water, sun glints, and the effects of the ripples are severe obstacles and impose limits to the processing and expected accuracy, and therefore few attempts are reported for orthophoto production over shallow waters (i.e. [127].

A recent work of Skarlatos and Savvidou [126] presents an iterative photogrammetric model for processing data over coastal sites, in order to produce precise and seamless orthophotos over land and shallow waters for survey detection, documentation and monitoring of coastal archaeological sites (Fig. 8). The method is based on the principle of using approximate depths for correcting the refraction effect, as Georgopoulos and Agrafiotis [127] introduced. However, Skarlatos and Savvidou [126] method is more sophisticated and the entire process is iterative, leading to better performance.

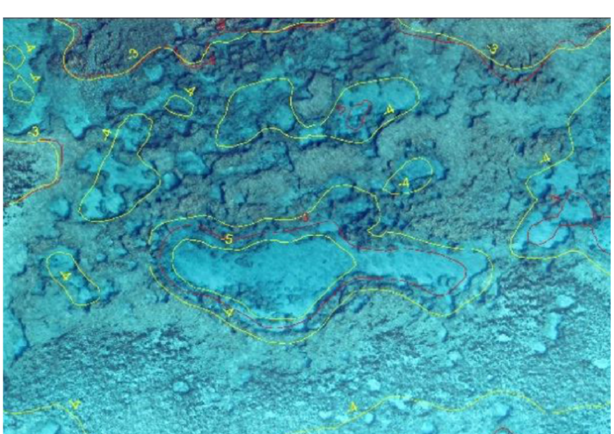

Fig. 8. Detail of the Agia Napa coastal site with bathymetric contours before (red) and after (yellow) the refraction corrections [126].

The potential of satellite imagery and remote sensing in underwater archaeology and shipwrecks localization in relatively shallow waters has been examined since the early 1980s [128]. Recently, a study describing a new methodology to detect the presence of submerged shipwrecks using ocean colour satellite imagery in turbid waters was presented by [129]. The methodology proposed is based on the generation of Particulate Matter (SPM) concentration signals from the wrecks that can be detected by high-resolution ocean colour satellite data such as Landsat-8 (Fig. 9). Full-coverage MBES 1 m gridded data served as reference data. Results suggest that SPM plumes are indicators that a shipwreck is exposed at the seabed and certainly not buried.

4.1.2. Mapping and Reconnaissance in deep water

Archaeological reconnaissance in deep water is much harder and requires very good clues on potential locations of searched targets together with their characteristics carried out through preliminary studies [5]. In particular, size and material are very important (obtained for example from historical information). A multi-resolution sonar based approach is generally used and considered as the most effective. Once the object has been located, photogrammetry or laser scanning from ROV or submarines can be used for visual inspection and surveying purposes (section 4.2.2). The multiresolution approach aims to find anomalies with respect to the overall expected topography of the seabed, looking for well distinguishable geometrical features and analysing the backscattered acoustic signal. Information about the target and seabed materials are of paramount importance in the interpretation of sonar signal (for example metallic objects reflect back much more than wooden shipwrecks). Objects with sizes ranging between those of a shipwreck up to small aircraft may be located using DSM models of the seabed with spatial resolutions comprised between 50–5 m. These resolutions can be easily obtained through hull mounted multibeam sonars. Smaller objects need towed systems like side scan sonars towed few metres off the ground to be discovered [130].

In particular, side scan sonar imaging is considered one of the most effective techniques for reconnaissance for both shallow and deep water due to the favourable geometry of the towed sensor, and for the capability to analyse the backscatter responses of submerged materials, both organic (wood and leather) and inorganic (metals, ceramics, glass and varying aggregate and ballast grades) [131].

New generation of MBES system also allow to analyse both bathymetric and backscattered data as shown in Plets et al. [132] who exploited the integration of these data to identify shipwreck sites surveys off the north coast of Ireland (Fig. 10).

All the aforementioned methodologies and systems are well-suited for detecting and mapping shipwrecks and other archaeological remains that lie fully or partly exposed above the sea floor. However, when it comes to obtaining more detailed information about potential findings buried within and covered by sea floor sediments different methods and systems are implemented that can penetrate the seafloor sediments either physically (probes, corers, water jets etc.) or by remote sensing through acoustic methods based on sub bottom profilers.

These systems provide an acoustic profile of a narrow section of the sub bottom beneath the path over which the device is being moved. The transducer produces pulses with a varying frequency according to the application, which is cone-shaped downwards. Parts of these signals are reflected off the seafloor surface, while other parts penetrate the seafloor. The theory at the basis of such techniques is far beyond the scope of this article [106,133].

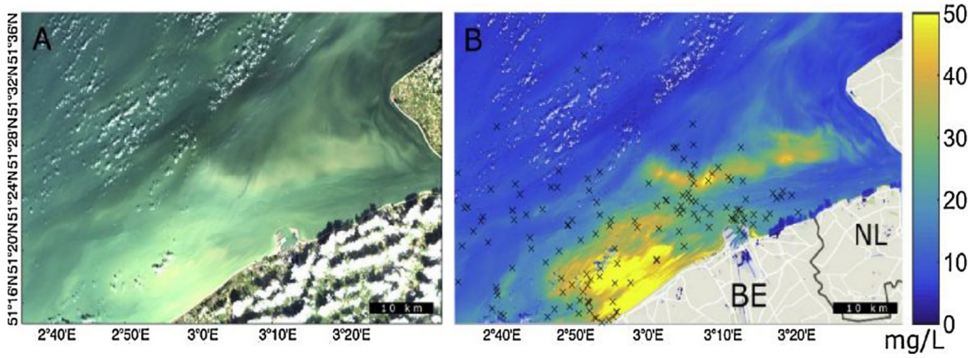

Fig. 9. A. Original Landsat-8 image taken on day 280 (2013) under spring tide conditions. B. Corresponding SPM concentration map. Black crosses indicate (mostly buried) shipwreck sites.

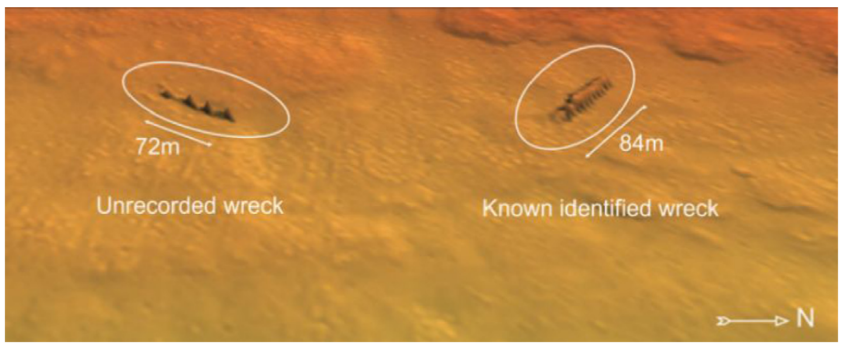

Fig. 10. MBES data are utilised for archaeological reconnaissance to detect shipwrecks [132].

4.2. *High resolution underwater 3D recording and mapping*

Highly detailed surveys are following the general mapping and reconnaissance methods for different purposes: a faithful documentation of newly found sites of archaeological significance; before, during and after an excavation process underwater; or for monitoring tasks. Due to the much greater spatial resolution required, typically in the order of some millimetres, sensors designed to work at short-range, within few metres from the subject, are utilised. Also, the availability of radiometric information along with 3D data about the surveyed objects becomes crucial for many diagnostics and interpretation tasks. To this end different image enhancement and colour correction algorithms have been proposed [134,135] and tested for their effectiveness in both clear and turbid waters [136–139]. In the most recent work presented by Mangeruga et al. [136], (5) different state of the art colour correction algorithms are tested on imagery from underwater archaeological sites in different environmental and illumination conditions. As for the general mapping, shallow and deep waters impose different constraints which influence the whole recording process.

4.2.1. *High resolution surveys for shallow waters*

In general, when the object is within few metres from the water surface, water caustics caused by refraction effects originated at the surface (section 2.1.1) can become a problem for all passive optical sensors, thus requiring the object to be surveyed with artificial illumination under overcast conditions or with the sun low on the horizon. The use of acoustic sensors in very shallow water is also problematic due to multipath errors and artefacts, requiring special algorithms and post processing strategies [140].

Besides lighting artefacts near the surface, shallow water can be more problematic for diver based photogrammetric acquisition due to the greater difficulty to control buoyancy [4,141,142].

In the literature, few cases of geometric recording of monuments using through water photogrammetric techniques have been reported so far. Special platforms for hoisting the camera have been used [122,143,144]. These applications have adopted some ways for correcting the refraction effect at the water surface. For mapping an underwater area, Elfick and Fryer [145] used a "floating pyramid" for lifting two cameras. The base of the pyramid was made of plexiglass and was placed on the water surface to create a flat air-water interface (Fig. 11a). A more contemporary application is reported in Butler et al. [146] for mapping the bottom of a river. The extracted DTM points have been corrected from refraction effects, based on a specially developed algorithm. A Plexiglas surface was again placed on the water surface for hosting the artificial control points and eliminate the effect of the water caustics. Recently, a work presented in Georgopoulos and Agrafiotis [127] reported a method for the correction of the refraction phenomenon in two-media (through air and water) photogrammetric techniques for the documentation of a submerged archaeological site at a depth ranging from 0.5 to 2 m. The accuracy levels achieved are adequate for a geometric documentation at a scale of 1:200.

Underwater photogrammetry for mapping the seabed has a long history, and for its flexibility represents one of the most used techniques in underwater archaeology, with first systematic experiments dating back to the sixties (Fig. 11b). These applications for underwater mapping were focused on orthophoto mosaic production, despite 3D measurements of the seabed could be already produced using standard photogrammetric methods normally used on land [147–149].

An early example of digital orthophoto mosaic to map a number of amphorae discovered in a sunken ship off the shore of Syria can be found in Murai et al. [150], where a digital elevation model using an analytical plotter was also produced for detailed 3D measurements of the amphorae (Fig. 11c). At the beginning of 2000, the advent of off-the-shelf digital cameras, waterproof housings

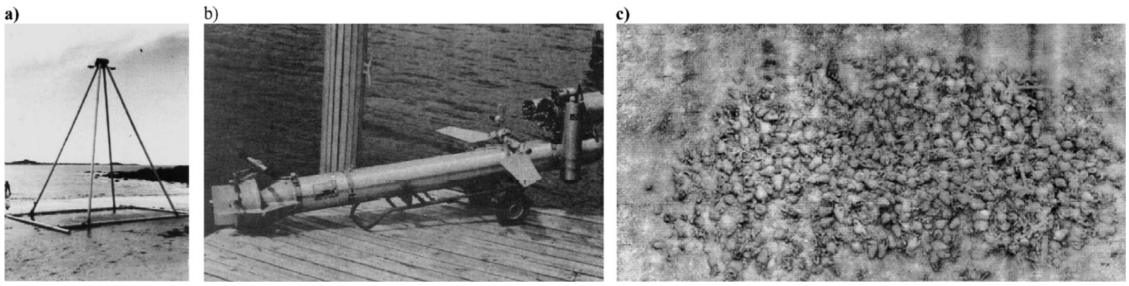

Fig. 11. Early photogrammetric systems and products: a) the "floating pyramid" used by Fryer [122] for through water image acquisitions; the "Pegasus" submersible system (piloted by a scuba diver) equipped with underwater cameras specifically designed for photogrammetric application [147]; an example of digital orthophoto mosaic to map a number of amphorae discovered in a sunken ship off the shore of Syria [150].

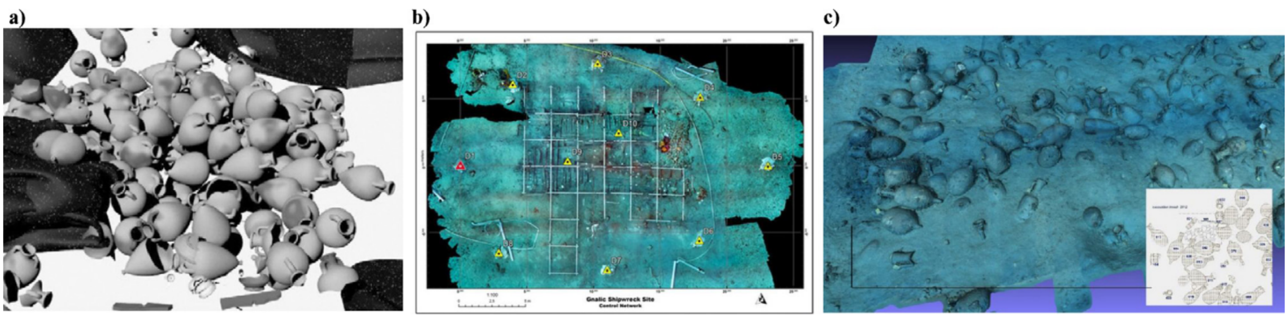

Fig. 12. Examples of digital products obtained through photogrammetric acquisition carried out by scuba divers: a: a 3D rendered view of digitally reconstructed amphorae over the underwater archaeological site [151]; b: an orthophoto of the excavation site with superimposed the surveyed control points [160]; c: a 3D textured model of an underwater excavation of a shipwreck [163].

and publicly available educational as well as low-cost commercial software for close range photogrammetry brought new significant works in archaeology, by simplifying the process of underwater 3D recording [142,151,152].

More recently, a large number of papers report applications of photogrammetry and computer vision for archaeological documentation within the limits of most recreational diving certifications (Fig. 12). These approaches consist of (i) an image acquisition carried out by divers along transects covering the areas of interest, similarly to what is done in aerial photogrammetry and (ii) an automatic processing pipeline based on SfM, Dense Image Matching (DIM), mesh generation and orthophoto production [153–155].

A similar approach is employed in Bruno et al. [156], for the documentation of an archaeological site in the underwater park of Baiae during experimental cleaning operations. Demesticha et al. [157] present a systematic procedure for the 3D mapping with uncalibrated cameras used during the excavation process of an ancient shipwreck lying at −45 m, thus beyond recreational diving certifications.

McCarthy and Benjamin [158] discuss the 3D results from trials in Scotland and Denmark at depths of up to 30 m. In Van Damme [159] a Dutch shipwreck site located between 16 and 20 m depth is recorded in 3D using an uncalibrated action camera. Due to the very poor water transparency, in some cases camera to object distance was kept as close as 20 cm, in order to collect images suitable for automated processing procedures. Yamafune et al. [160] present a methodology to record and reconstruct the wooden structures of a 19th-century shipwreck in southern Brazil and of a 16th-century shipwreck in Croatia. In Zhukovsky et al. [161] a case study of application of photogrammetric techniques for archaeological field documentation record in course of underwater excavations of the Phanagorian shipwreck is reported. In Balletti et al. [162] a survey and 3D representation of two Roman shipwrecks using integrated surveying techniques for documentation of underwater sites is described. In Diamanti and Vlachaki [163] the implementation of photogrammetric and geodetic techniques used for acquisition and processing of collected data is presented, in order to generate 3D models for six different wrecks found at medium depths (22–47 m) in the South Euboean Gulf in Greece. Most of the aforementioned approaches use the commercially available software application Agisoft Photoscan [164]. There are few reports in the literature using open source software for such applications [165,166] where, for the reconstruction process, the Bundler software [167] was used to orient the images and retrieve the camera calibration parameters. The successive DIM step was then performed using the PMVS (Patch-based Multi-View Stereo) software [168].

With the aim to create high-resolution 2D photo-mosaics and detailed 3D textured models of a large submerged archaeological site, Henderson et al. [169] introduced a system that takes geo-referenced stereo imagery from a diver-propelled platform and combines it with SLAM.

As far as active optical systems are concerned, in the work presented by Petriaggi and de Ayala [170], the development and experimentations of two underwater laser scanners is described. The experimentations took place in shallow water in the Underwater Park of Baiae–Marine Protected Area, Naples in the context of an underwater restoration project.

For semi-submerged still objects different techniques can be applied to obtain a joint seamless 3D model. The used techniques may rely on surveying reference points located both under and above the water in the same coordinate system or using a direct georeferencing method based on GNSS/INS integration as it was described for mobile mapping platforms. In Moisan et al. [140] old canal tunnels in service for commercial navigation and boating are surveyed using a combination of TLS for the part above the water and 3D mechanical scanning sonar (MSS) from static positions for the submerged part. Due to the lack of overlap between the two surveyed parts, partly immersed ladders of known geometrical characteristics are used (Fig. 13a). In Menna et al. [171], a photogrammetric method, initially developed for marine engineering applications [141,172] was applied to a semi-submerged

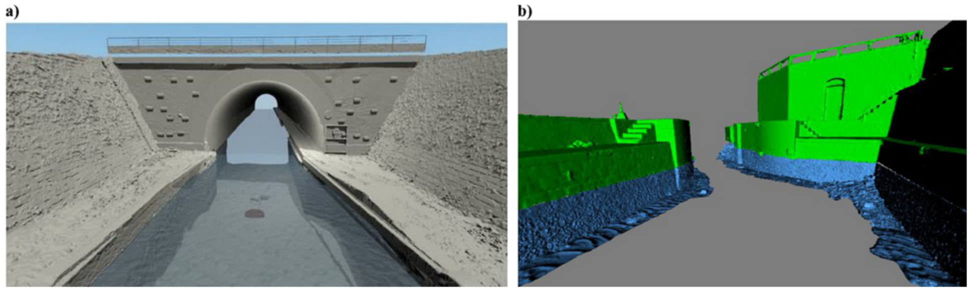

Fig. 13. Examples of 3D models of partly submerged structures of cultural heritage interest: a: an old canal tunnel in service for commercial navigation and boating surveyed using a combination of TLS for the part above the water and 3D mechanical scanning sonar for the submerged part; b: an old basin surveyed with a combined photogrammetric approach [58].

archaeological structure (Fig. 13b). The process, consists of carrying out, two separate photogrammetric surveys, each in their respective media, i.e. one in air above the water level and one under the water. Through several special rigid targets that are partially immersed, rigid transformations are computed through a minimisation process to combine the two separate surveys in a unique reference system. The process provides a seamless model of the structure both above and under the water.

Operations carried out by scuba divers impose several safety related constraints. Limited bottom time (to prevent decompression sickness – DCS), narcotic effects of nitrogen (deeper than 30 m) and central nervous system (CNS) oxygen toxicity may require several divers and dives for the same surveying campaign, thus increasing costs significantly. For this reason, robotised platforms like ROV and AUV have been used, especially to cover larger areas or access dangerous sites. For example, a novel approach using both an AUV and a diver-controlled stereo imaging platform (for very shallow water) was presented by Johnson-Roberson et al. [173] in order to document the submerged Bronze Age city at Pavlopetri, Greece. The survey resulted in a 3D reconstruction covering 26,600 m^2 at a spatial resolution of 2 mm/pixel; in Clark et al. [174] and White et al. [175] underwater robot systems enabled with several mapping and localization technique were used to explore and map ancient cisterns located on the islands of Malta and Gozo. A small sonar-equipped remotely operated vehicle (ROV) was deployed into these cisterns to obtain both video footage and sonar range measurements (Fig. 14a).

4.2.2. High resolution surveys for deep waters

While in shallow water the use of robotised platforms may be an option, exceeding the recreational diving limits on depth and bottom time gives very limited choice. ROV and AUV systems can perform most of the tasks needed for photogrammetric purposes, thus limiting the use of skilled and specialised technical divers to few special cases. AUV and ROV can cover large underwater areas with precise navigation in a time-efficient manner without any contact and overcoming the limitations posed by divers. Captured data by these systems in archaeological 3D modelling and mapping applications consist mainly of optical data.

Typically, the imagery taken from an AUV or a ROV system is acquired by following the principles of aerial photogrammetry, then it is generally processed using a SfM and MVS processing pipeline [176–179].

In Ludvigsen et al. [179] a support frame enclosing the excavation site is utilised to constrain and drive the ROV motion in a plane (Fig. 14b). A similar procedure to the SfM-MVS processing is applied here. Additionally, the extracted feature points are matched and tracked into overlapping stereo-image pairs. The resulting information is integrated with additional navigation sensor data, which is usually a depth sensor, a velocity sensor and attitude sensors in order to implement the SLAM algorithm [178] and compute the trajectory of the platform.

This estimated trajectory and the 3D points resulting from the SfM-MVS processing are then used to reconstruct a global feature map of the underwater scene.

Bingham et al. [180] developed techniques for large-area 3D reconstruction area which were applied using an AUV. These techniques extracted 3D bathymetry gridded at 5 cm resolution for a 4th c. B.C. shipwreck site off the Greek island of Chios in the north eastern Aegean Sea. Mahon et al. (2011) [181] also presented a vision-based underwater mapping system for archaeological use in the same area.

The system produced three-dimensional textured models allowing for further archaeological research to be performed.

In Bosch et al. [182] an omnidirectional underwater camera in AUV was used for a survey over a shipwreck. In Drap et al. [54] an approach based on photogrammetry for surveying the Roman shipwreck Cap Bénat 4, at a depth of −328 m using an ROV is presented (Fig. 14c). This hybrid technique provides real time results, sufficient for piloting the ROV from the surface vessel and ensures a millimetric precision on the final 3D results; the work in Drap et al. [183] presents a photogrammetry-based approach for deep-

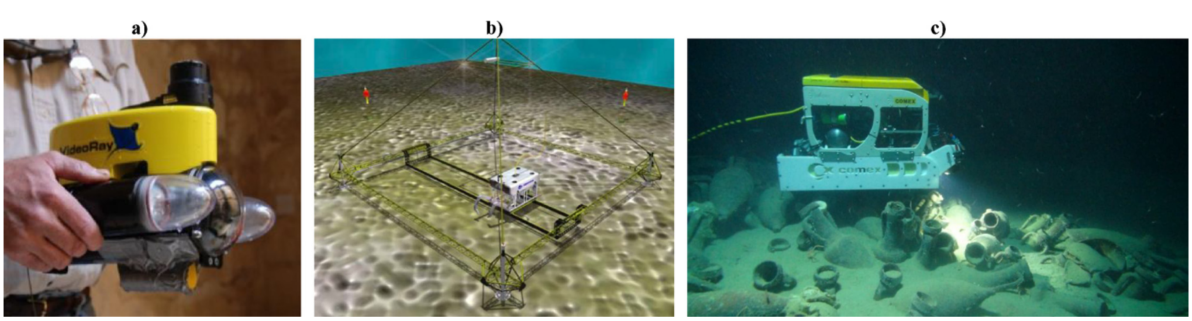

Fig. 14. Examples of ROVs systems used for 3D recording within archaeological projects: a: a small remotely operated vehicle (ROV) used to explore map cisterns to obtain both video footage and sonar range measurements [174]; b: a schematic view of the support frame used by Ludvigsen et al. [179] to drive the ROV during the image acquisition; c: the ROV Apache, surveying Cap Benat 4 wreck at a depth of 328 m [54].

sea underwater surveys conducted from a submarine and guided by knowledge-representation combined with a logical approach (ontology). A low-resolution 3D model is obtained in real-time, followed by a very high-resolution 3D model produced back in the laboratory. In the work presented in Roman et al. [184], high resolution bathymetric maps of various underwater archaeological sites in water depths between −50 and −400 m and different water clarity conditions are created by using a ROV equipped with cameras, laser and a multibeam sonar. Comparison between the results of the three different sensors indicated that in every case the laser and multibeam results were consistent while in stereo imaging the point density is also highly dependent on scene texture. However, this is a common problem in stereo imaging and SfM processing and particularly challenging in underwater images having low contrast in sediment covered wreck sites.

5. Concluding remarks

Underwater cultural heritage is rich and totally unprotected. It is actually Heritage-at-(great)-Risk! Recording, documenting and, ultimately, protecting underwater cultural heritage is an obligation of mankind and dictated by the International Conventions. It requires a broad range of scientific and professional expertise as conditions underwater are hostile for humans and normal equipment; consequently, good knowledge of the adverse conditions and of the limitations imposed on operations is of utmost importance.

Depending on the principal aim of the investigation such as whether the underwater surveying is for reconnaissance, mapping or high-resolution monitoring, different technologies may be utilized, sometimes interchangeably, allowing some flexibility in the data acquisition, sometimes exclusively, thus requiring strict project planning and budget constraints (e.g. technology requiring a supply vessel for deployment).

Despite technology progresses in 3D digital recording and mapping techniques, 3D data accuracy and resolution provided by the sensors described in Section 3, are highly dependent on various external parameters of which the most important is the distance to the object. As a general rule, the larger the distance from the sensor to the object the worse the accuracy and resolution. This simple geometrical rule is at the basis of many reconnaissance activities at sea such as for example when searching for a particular target underwater, like a shipwreck. Assumption and a priori knowledge about the object of study is fundamental in these cases.

Submerged optical sensors are unbeatable in terms of spatial resolution but are seldomly used for surveying large seafloor areas as they are limited to work only within few metres from the object due to water turbidity (even only centimetres in some seas or lakes) and light absorption and scattering. Additionally, the selection of a sensor and related processing techniques with respect to another is dictated by other several factors, the most important are the following:

- the characteristics of the object to be surveyed: object material and colour and its orientation, are important factors as well as the buried percentage which affects the general planning of surveying process and the methods to be used. The partial or total coverage of the object by aquatic plants is also an issue in most of the cases since they cause occlusions and cause artefacts in the acquired data due to their motion caused by the swell of the ocean;
- local physical characteristics of water such as depth, turbidity and temperature as well as seabed relief and characteristics (mud, rocks etc.) also affect the selection of the right sensor and related processing techniques. Depths more than 50 m lead to AUV and ROV usage in most of the cases that depend on optical sensors. Very shallow water may be mapped with bathymetric LiDAR sensors or airborne and spaceborne imagery if the water turbidity allows it;
- finally, weather and sea conditions such as wind, waves, currents and floating objects (i.e. marine debris particles etc.) may affect the surveying process planning and results or postpone a survey either it being based on aerial, sea surface or underwater platforms.

This paper presented an extensive review over the sensors and the methodologies used in archaeological underwater 3D recording and mapping and has provided the necessary framework and background knowledge for carefully planning a reconnaissance or recording campaign for underwater cultural heritage.

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Glossary

AGISC: Ad-hoc Group on the Impacts of Sonar on Cetaceans and Fish
ALB: Airborne Laser Bathymetry
ALS: Airborne Laser Scanner
AUV: Autonomous Underwater Vehicle
CHIRP: Compressed High-Intensity Radiated Pulse
DIM: Dense Image Matching
DSLR: Digital Single-Lens Reflex
DSM: Digital Surface Model
DTM: Digital Terrain Model
GNSS: Global Navigation Satellite System
ICOMOS: International Council on Monuments and Sites
IMU: Inertial Measurement Unit
ILA: International Law Association
LiDAR: Light Detection And Ranging
MBES: Multibeam Echo Sounders

MLS: Mobile Laser Scanner
MVS: Multi-View Stereo
RADAR: RAdio Detection And Ranging
ROV: Remotely Operated Underwater Vehicle
SBES: Single Beam Echo Sounder
SCUBA: Self-Contained Underwater Breathing Apparatus
SfM: Structure-from-Motion
SLAM: Simultaneous Localization and Mapping
SONAR: SOund Navigation And Ranging
TLS: Terrestrial Laser Scanners
ToF: Time of Flight
UAV: Unmanned Aerial Vehicle
UCH: Underwater Cultural Heritage
UN: United Nations
UNESCO: United Nations Educational, Scientific and Cultural Organization
UNCLOS: United Nations Convention on the Law of the Sea